Advanced Oxygen-Hydrocarbon Rocket Engine Study

Contract NAS 8-33452
Bi-Monthly Progress Report 33452M-2
February 1980

Prepared For:
National Aeronautics And Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

By:
C. J. O'Brien

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FOREWORD

This is the second bi-monthly progress report submitted for the Advanced Oxygen - Hydrocarbon Rocket Engine Study per the requirements of Contract NAS 8-33452. The work is being performed by the Aerojet Liquid Rocket Company for the NASA-Marshall Space Flight Center. The contract was issued on 15 October 1979. The program inclusive dates for period of performance are 15 October 1979 through 15 February 1981. This report covers the period from 1 December 1979 to 31 January 1980.

The program consists of parametric analysis and design to provide a consistent engine system data base for defining advantages and disadvantages, system performance and operating limits, engine parametric data, and technology requirements for candidate high pressure LO_2/Hydrocarbon engine systems.

The NASA-MSFC Project Manager is Mr. R. J. Richmond. The ALRC Program Manager is Mr. J. W. Salmon and the Project Engineer is Mr. C. J. O'Brien.

Contributors to this bi-monthly report are:

G. D. Aldrich - Structural Analysis
R. A. Hewitt - Thermodynamic Design Analysis
S. Kent - Engine/Vehicle Analysis and Engine Weight Analysis

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I. INTRODUCTION

In the decade of the 1980's and beyond, the nation's expanding space operations may require an improved surface-to-orbit transportation system using advanced booster vehicles which have increased performance and capability compared to the current space shuttle concept. The mixed-mode propulsion principle clearly indicates the potential performance advantages of using high density-impulse rocket propellants in such large ΔV applications. For this reason, hydrocarbon fuels exhibiting increased density relative to liquid hydrogen (LH_2), at the penalty of lower specific impulse, are being considered for the booster propulsion system of space shuttle improvements and derivatives as well as for single-stage-to-orbit and two-stage-to-orbit heavy-payload vehicles.

Preliminary identification and evaluation of promising liquid oxygen/hydrocarbon (LO_2/HC) rocket engine cycles is desirable to produce a consistent and reliable data base for vehicle optimization and design studies, to demonstrate the significance of propulsion system improvements, and to select the critical technology areas necessary to realize such advances.

It is the purpose of this study to generate a consistent engine system data base for defining advantages and disadvantages, system performance and operating limits, engine parametric data, and technology requirements for candidate high pressure LO_2/HC engine systems. The study will also synthesize optimum LO_2/HC engine power cycles and generate representative conceptual engine designs for a specified advanced surface-to-orbit transportation system.

To accomplish the program objectives, the study is composed of four major technical tasks and a reporting task. These tasks and summarized objectives are:

I, Introduction (cont.)

A. TASK I - ENGINE CYCLE CONFIGURATION DEFINITION

Formulate and assess families of high chamber pressure LO_2/HC engine cycles.

B. TASK II - ENGINE PARAMETRIC ANALYSIS

Generate performance, weight, and envelope parametric data for viable concepts based upon historical data and conceptual evaluations.

C. TASK III - ENGINE/VEHICLE TRAJECTORY PERFORMANCE ASSESSMENT (ENGINE SCREENING)

Conduct a preliminary comparison of selected engine cycles utilizing a simplified vehicle trajectory performance model.

D. TASK IV - BASELINE ENGINE SYSTEMS DEFINITION

Prepare preliminary designs of two baseline engine configurations. Conduct heat transfer, turbomachinery, combustion stability, structural, and controls analysis of the baseline engines and components. Conduct a parametric sensitivity analysis including the effects of turbine temperature and number of usable life cycles. Provide the appropriate data in a format suitable for use in vehicle application analyses.

E. TASK V - REPORTING

Provide informal bi-monthly technical and fiscal progress reports, hold program reviews at NASA/MSFC and prepare a final report.

II. TECHNICAL PROGRESS SUMMARY

The overall progress on the program is indicated in Figure 1.

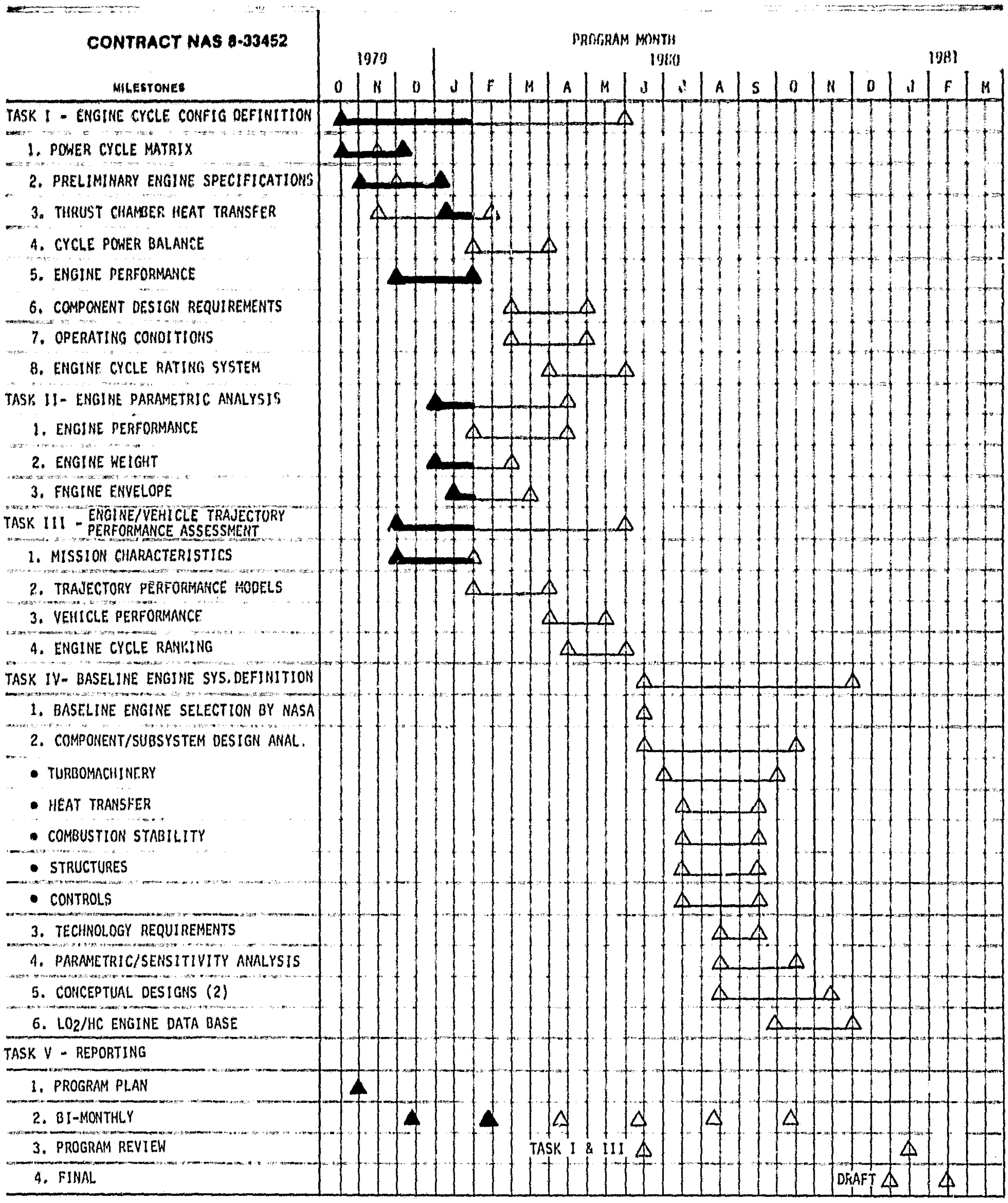

Figure 1. Major Milestone Schedule

II, Technical Progress Summary (cont.)

A. TASK I - ENGINE CYCLE CONFIGURATION DEFINITION

1. Power Cycle Matrix and Engine Specifications

Preliminary specifications were prepared for the thrust chamber assembly (TCA) of each of the families of candidate cycles given previously (cf. Bi-Monthly Progress Report 33452M-1, December 1979). The preliminary TCA specifications are given in Tables I and II, respectively, for LO_2/RP-1 and LO_2/LCH_4 engines at chamber pressures from 1000 to 5000 psia and at selected area ratios.

Additional specification parameters, required for open loop (gas generator or bleed) cycles, are listed in Table III. These parameters are derived for the specific engine operating point through a power balance calculation establishing the required pump discharge pressures.

Typical preliminary power cycle results are summarized in Table IV. A more complete matrix will be assembled when the heat transfer results (coolant pressure drop) are available to perform a realistic power balance for each cycle. At this time cycle rating parameters (such as coolant limit Pc, power limit Pc, engine weight, interpropellant seal requirement, turbine coking problem, and mission payload capability) will be included in the matrix to aid in the selection of the optimum cycles.

2. Thrust Chamber Heat Transfer

This subtask includes four related efforts: (1) definition of chamber geometry, (2) selection of material properties, (3) establishment of structural criteria, and (4) parametric chamber/nozzle cooling analysis. The first three efforts have been completed, and the fourth effort has been initiated.

TABLE I

LO_2/RP-1 THRUST CHAMBER ASSEMBLY PRELIMINARY SPECIFICATION

PARAMETER					
Chamber Pressure, psia	5000	4000	3000	2000	1000
Thrust, sl, lbf	600,000	600,000	600,000	600,000	600,000
Thrust, vac, lbf	657,898	661,103	667,488	660,681	710,369
Mixture Ratio	2.9	2.9	2.8	2.8	2.8
Area Ratio	60	50	41	24	20
ODE Is, sl, sec	336.8	331.9	324.5	317.4	290.3
ODE Is, vac, sec	369.3	365.7	361.0	349.5	343.7
Is Efficiency, %	97	97	97	97	97
Deliv. Is, sl, sec	326.7	321.9	314.8	307.9	281.6
Deliv. Is, vac, sec	358.2	354.7	350.2	339.0	333.4
Total Flow Rate, lb/s	1836.57	1863.68	1906.18	1948.82	2130.75
LO_2 Flow Rate, lb/s	1365.65	1385.82	1404.56	1435.98	1570.03
Fuel Flow Rate, lb/s	470.92	477.87	501.63	512.85	560.72
c*, ft/s	5930	5915	5924	5897	5850
Throat Area, in^2	67.70	85.66	116.99	178.59	387.42
Throat Diam., in.	9.28	10.44	12.20	15.08	22.21
Exit Area, in^2	4062	4283	4738	4251	7748
Exit Diam., in	71.92	73.84	77.67	73.57	99.33
Exit Pressure, psia	7.79	7.92	7.50	10.0	6.41

TABLE II

LO_2/LCH_4 THRUST CHAMBER ASSEMBLY PRELIMINARY SPECIFICATION

PARAMETER					
Chamber Pressure, psia	5000	4000	3000	2000	1000
Thrust, sl, lbf	600,000	600,000	600,000	600,000	600,000
Thrust, vac, lbf	628,646	661,462	666,667	660,662	671,322
Mixture Ratio	3.5	3.5	3.5	3.5	3.2
Area Ratio	60	50	40	24	13
ODE Is, sl, sec	345.6	350.7	333.9	326.4	307.9
ODE Is, vac, sec	362.1	375.6	371.0	359.4	344.5
Is Efficiency, %	97	97	97	97	97
Deliv. Is, sl, sec	335.2	330.5	323.9	316.6	298.7
Deliv. Is, vac, sec	351.2	364.3	359.9	348.6	334.2
Total Flow Rate, lb/s	1789.81	1815.55	1852.52	1895.09	2008.95
LO_2 flow Rate, lb/s	1392.07	1412.09	1440.85	1473.96	1530.63
Fuel Flow Rate, lb/s	397.73	403.45	411.67	421.13	478.32
c*, ft/s	6119	6106	6088	6062	6095
Throat Area, in^2	68.08	86.14	116.85	178.53	380.57
Throat Diam., in	9.31	10.47	12.20	15.08	22.01
Exit Area, in^2	4085	4307	4674	4285	4947
Exit Diam., in	72.12	74.05	77.14	73.86	79.37
Exit Pressure, psia	7.44	7.55	7.60	10.0	10.0

TABLE III

ADDITIONAL SPECIFICATION PARAMETERS FOR OPEN-LOOP CYCLES

PARAMETER
Thrust (Gas Generator), sl, lbf
Thrust (Gas Generator), vac, lbf
Is (Gas Generator), sl, sec
Is (Gas Generator), vac, sec
Total (Gas Generator) Flow Rate, lb/s
LO_2 (Gas Generator) Flow Rate, lb/s
Fuel (Gas Generator) Flow Rate, lb/s
Thrust (Engine), sl, lbf
Thrust (Engine), vac, lbf
Mixture Ratio (Engine)
Is (Engine), sl, sec
Is (Engine), vac, sec
Total Flow Rate (Engine), lb/s

TABLE IV

PRELIMINARY POWER CYCLE MATRIX FOR LO_2/Hc ENGINES

ENGINE CYCLE	FUEL	COOLANT	TURBINE DRIVE	$\dot{W}_{GG}/\dot{W}_{TCA}$ %	ΔIs (SL) sec (%)	P_c psia	P_D psia	ENGINE MR
(A) Gas Gen.	RP-1	RP-1	RP-Rich	9.4 2.2	-20.8 (-6.5) -5.3 (-1.9)	4000 1000	5512 1282	2.33 2.65
(B) Gas Gen.	RP-1	LO_2	RP-Rich	10.9	-22.2 (-6.9)	4000	6385	2.26
(C) Gas Gen.	LCH_4	LCH_4	CH_4-Rich	8.2	-16.5 (-4.8)	4000	5370	2.90
(D) Stg. Comb.	RP-1	RP-1	RP-Rich	0	0	3000 2000 1000	9331 4219 1729	2.80
(E) Stg. Comb.	RP-1	LO_2	RP-Rich	0	0	3000	9944	2.80
(F) Stg. Comb.	RP-1	RP-1	O_2-Rich	0	0	4000	10868	2.90
(G) Stg. Comb.	RP-1	LO_2	O_2-Rich	0	0	4000	15546	2.90
(H) Stg. Comb.	LCH_4	LCH_4	CH_4-Rich	0	0	3000	8668	3.50
(I) Stg. Comb.	LCH_4	LCH_4	CH_4- & LO_2-Rich	0	0	4000	11371	3.50
(J) Gas Gen.	RP-1	LH_2	H_2-Rich	1.5	-1.1 (-0.3)	4000	4777	-
(K) Gas Gen.	RP-1	LH_2	O_2-Rich	15.7	-31.8 (-9.9)	4000	5804	-
(L) Ex. Bleed	RP-1	LH_2	H_2	1.5	-1.6 (-0.5)	4000	4777	-
(M) Stg. Comb.	RP-1	LH_2	H_2-Rich	0	1.0 (0.4)	1000	2659	-
(P) Stg. Comb.	RP-1	LH_2	H_2- & O_2-Rich	0	1.0 (0.3)	2000	5306	-
(Q) Stg. Comb.	RP-1	LH_2	H_2-, RP-, & O_2-Rich	0 0	1.1 (0.4) 1.1 (0.4)	3000 2000	6737 3667	- -
(R) SC/EB	RP-1	LH_2	O_2-Rich & H_2	1.0	0.7 (0.2)	2000	3393	-
(S) D-T SC/GG	RP-1	LH_2	H_2- & O_2-Rich	1.4	-0.5 (-0.2)	4000	8089	-
(T) D-T SC/GG	LCH_4	LH_2 & LCH_4	H_2- & O_2-Rich	1.5	-0.8 (-0.3)	4000	7983	-

A comparison of existing rocket engines over a chamber pressure range of three orders-of-magnitude and a thrust range over eight orders-of-magnitude leads to the following relationships for contraction ratio, CR, and chamber length, L':

Liquid-Liquid	Liquid-Gas
$\log CR = -0.0715 \log F + 0.689$	3.0
$\log L' = 0.23 \log (F/Pc) + 0.85$	$\log L' = 0.23 \log (F/Pc) + 0.621$

The contraction ratio for a liquid-liquid injection-state engine varies, by the equation, from 2.0 at F = 200,000 lbF to 1.8 at F = 1,500,000 lbF, while the CR for a liquid-gas engine is assumed constant at 3.0 over the same range. The chamber lengths (in inches) for liquid-liquid injection are given by the equation:

Thrust, lbF	Chamber Pressure, psia 1000	5000
200,000	24	17
1,500,000	38	26

The corresponding chamber lengths (in inches) for liquid-gas injection are:

Thrust, lbF	Chamber Pressure, psia 1000	5000
200,000	14	10
1,500,000	23	16

It is seen that the conventional liquid-gas chamber lengths are, in general, considerably shorter than the corresponding liquid-liquid chamber lengths. This shorter chamber and larger contraction ratio for

gas-liquid systems is the result of a number of tradeoffs involving weight, performance, cooling and combustion stability.

The properties of the candidate materials for the thrust chamber and nozzles have been used to obtain the maximum allowable stress and strain for an assumed hold time and number of required life cycles. The hold time is based on 250 seconds LO_2/hydrocarbon engine operation per flight and 100 flights (cycles) with a safety factor of four. Therefore,

$$t_{HOLD} = \frac{250 \times 100 \times 4}{3600} = 27.8 \approx 30 \text{ hours}$$

Figures 2 through 5 summarize the material envelopes for zirconium copper and Inconel 718 to be utilized in the heat transfer parametrics. Some recently received NASA/LeRC data appear to indicate that the data in the figures are somewhat pessimistic, and modifications may be necessary to obtain a better estimate of life cycles. Since the purpose of this task is to parametrically evaluate different engine cycles, it is important to maintain a consistent set of data. The relative rating of each cycle should remain essentially the same with any reasonable set of data. In Task IV, however, it will be required to utilize the latest materials and structures data in the preparation and analysis of the preliminary designs.

B. TASK II - ENGINE PARAMETRIC ANALYSIS

The engine weight and envelope subtasks have been initiated. Baseline engine weight breakdown statements for staged combustion and gas generator cycles are given in Table V for both LO_2/RP-1 and LO_2/LCH_4 engines. The component weights are considered to be off-the-shelf or 1980 state-of-the-art weights. They are consistent with SSME, Titan I, Titan II, and H-1 weight technology.

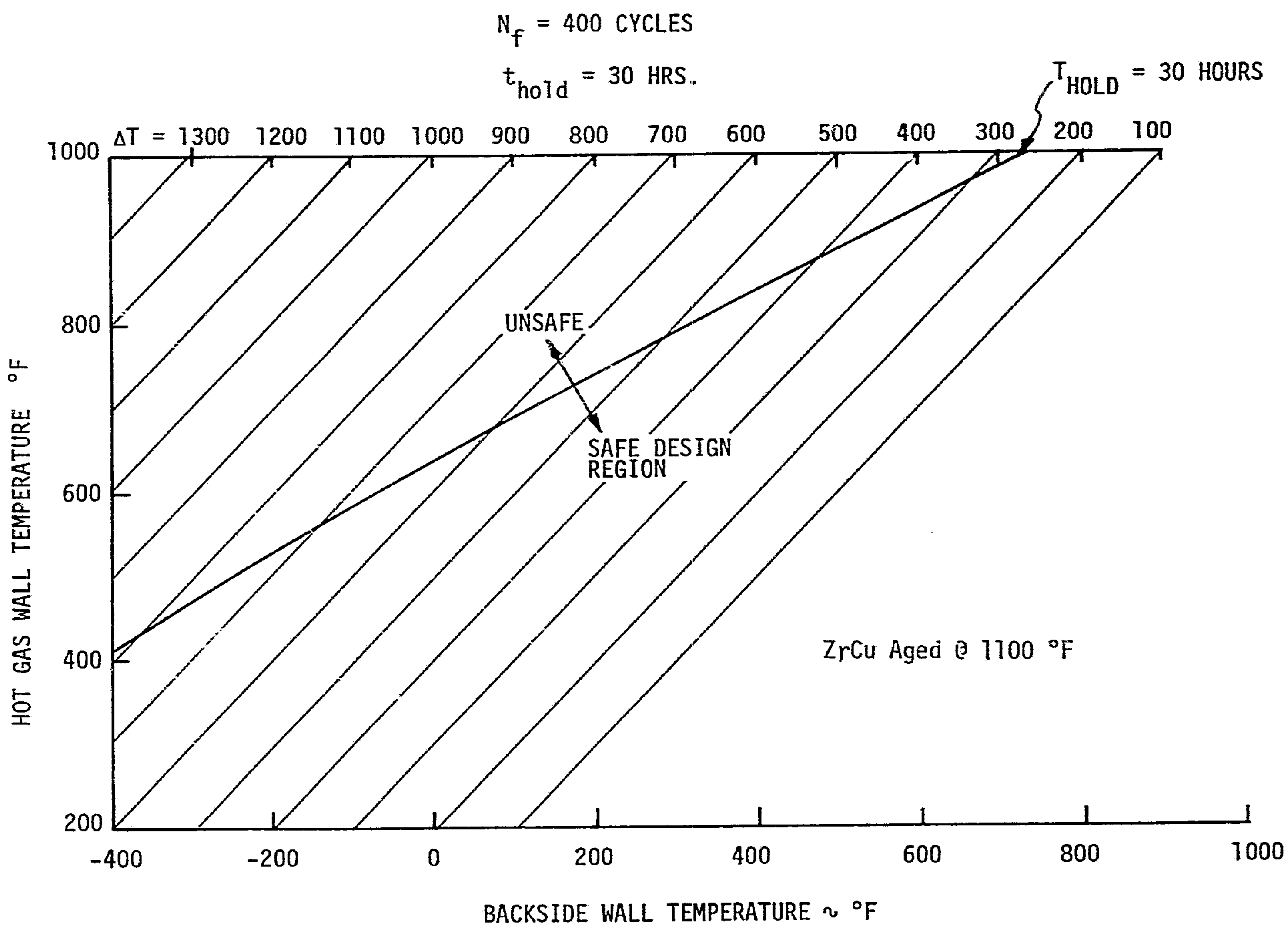

Figure 2. ZrCu Allowable Hot Gas Side Wall Temperature vs Backside Wall Temperature

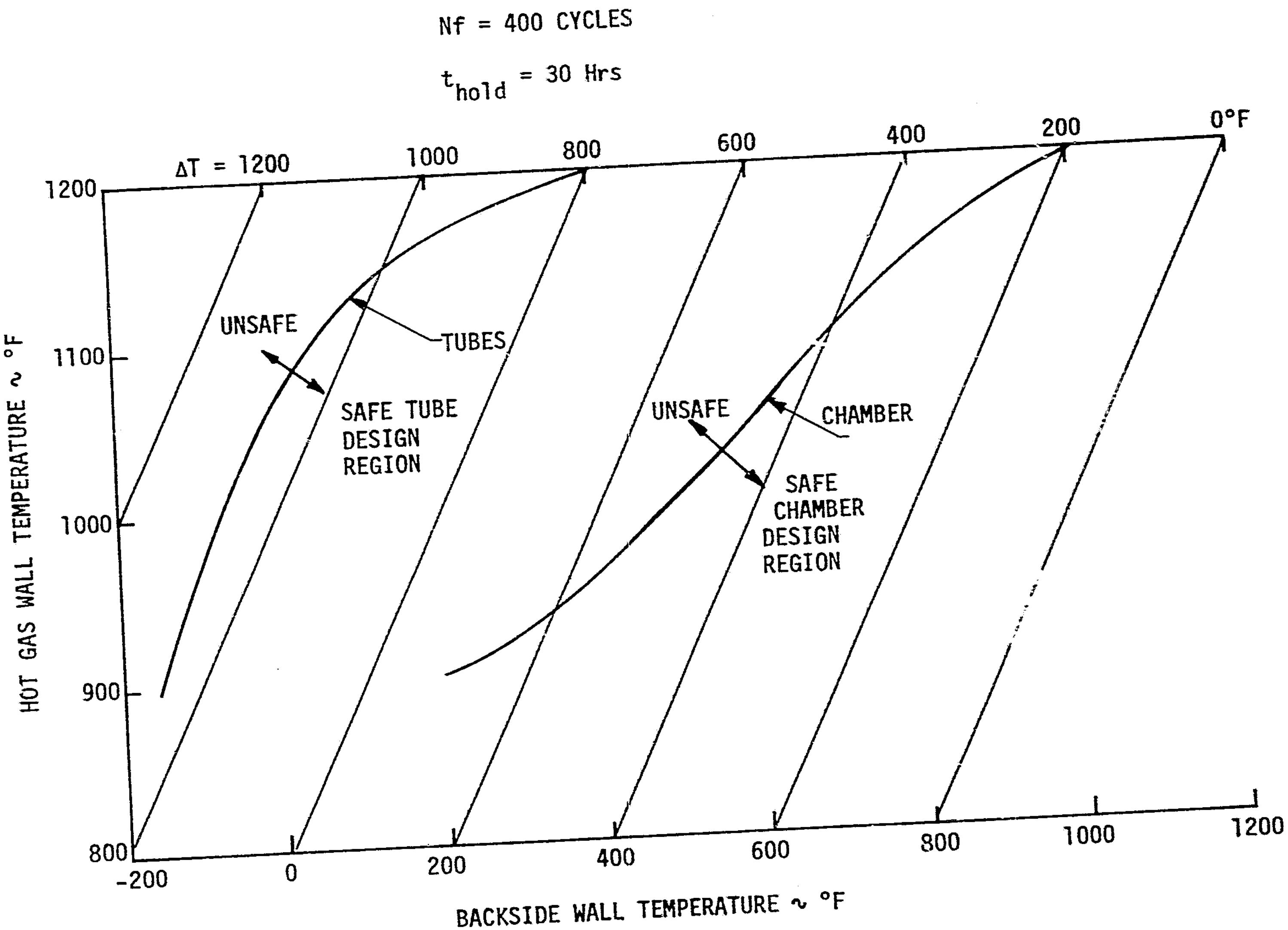

Figure 3. Inconel 718 Allowable Hot Gas Side Wall Temperature vs Backside Wall Temperature

$$\ell/t \leq \left(\frac{2F_{ALLOW}}{\Delta P}\right)^{1/2}$$

WHERE $\Delta P = |P_{cool} - P_c|$

$\Delta P = 1000$ psi

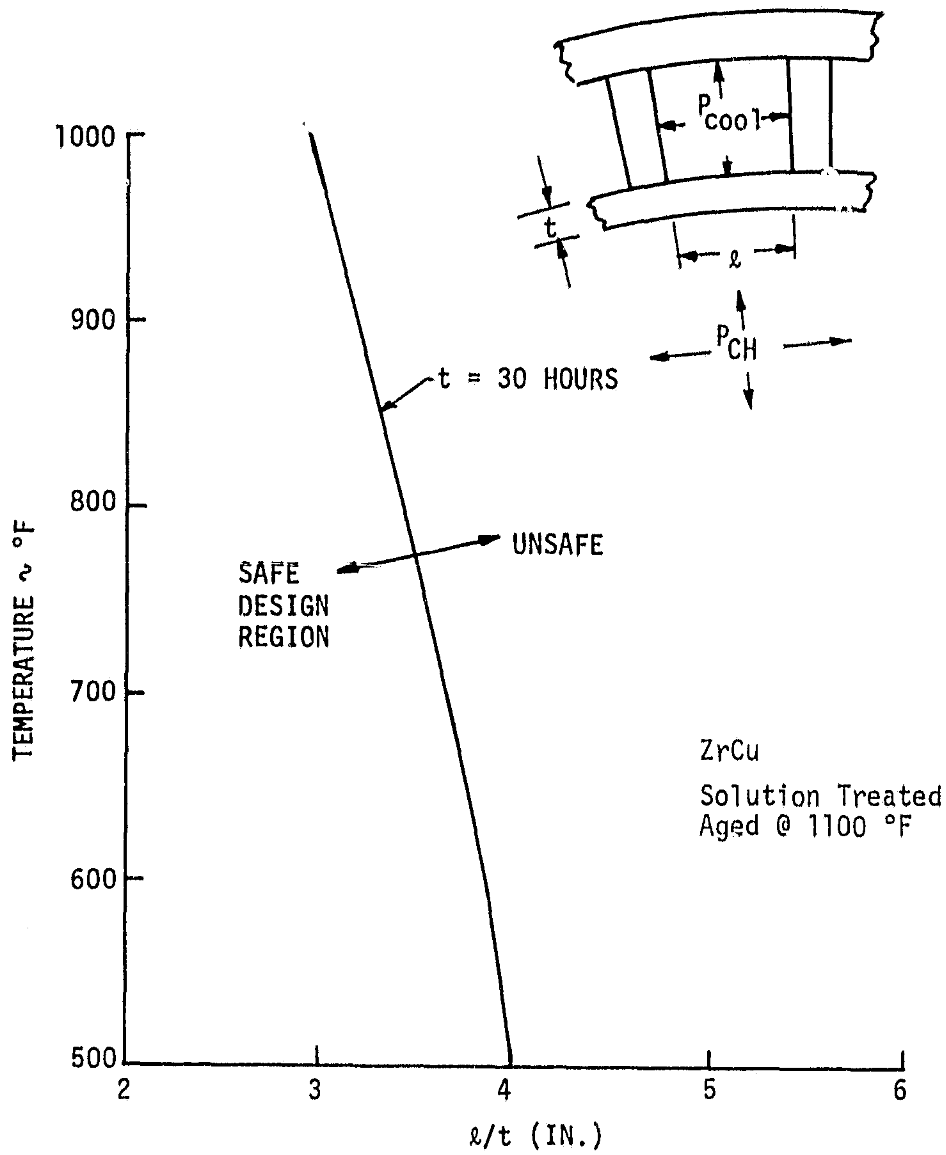

Figure 4. ZrCu Allowable Channel ℓ/t vs Hot Gas Wall Temperature

P_{COOL} = 1000 PSI

$R/t \leq F_{ALLOW}/P_{COOL}$ (SOLID LINE)

or $\leq \frac{.24}{\alpha \Delta T}$ (DASHED LINE)

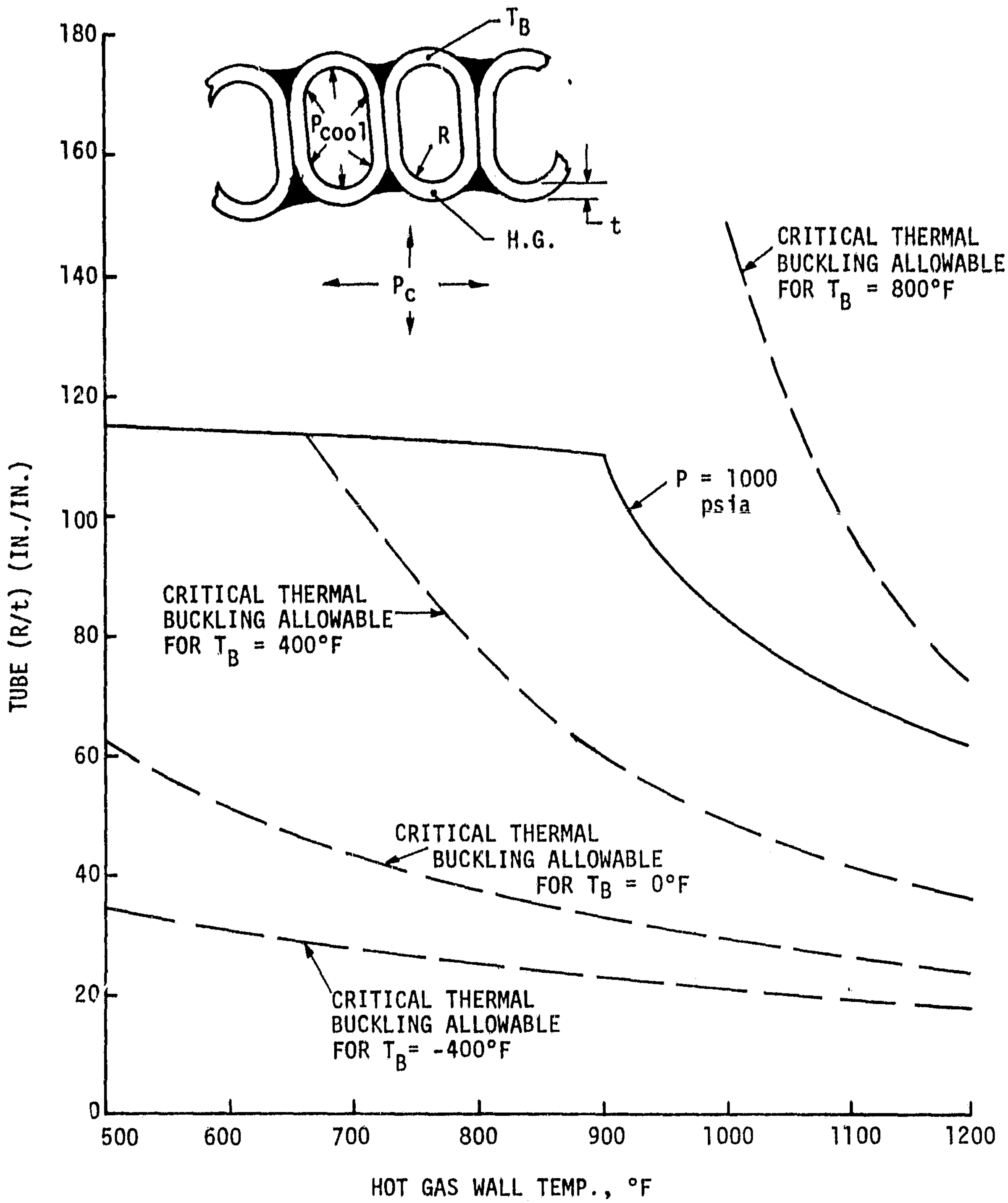

Figure 5. Inconel 718 Allowable Tube R/t vs Hot Gas Wall Temperature

TABLE V

LOX/HDF BASELINE ENGINE WEIGHT BREAKDOWN

	LOX/RP-1		LOX/CH_4	
	STAGED COMBUSTION	GAS GENERATOR	STAGED COMBUSTION	GAS GENERATOR
F_B (Thrust, lb)	600,000	600,000	600,000	600,000
P_{C_B} (Chamber Pressure, psia)	4000	4000	4000	4000
ϵ_B (Area Ratio)	50:1	50:1	50:1	50:1
ϵ_{ATTB} (Attached Area Ratio)	8:1	8:1	8:1	8:1
A_{TB} (Throat Area, in.^{2})	85.66	85.66	86.14	86.14
(All Weights in lbs)				
WGB (Gimbal)	207	207	207	207
WMISCB (Miscellaneous)	437	437	437	437
WINJB (Injector)	656	656	656	656
WTCNB (Nozzle)	420	420	422	422
WCCB (Thrust Chamber)	226	226	227	227
WPBOB (Ox Rich Preburner)	224	-	224	-
WPBFB (Fuel Rich Preburner)	181	20	181	20
WVOB (Oxidizer Valves & Actuators)	325	325	331	331
WVFB (Fuel Valves & Actuators)	82	82	131	131
WBPOB (Oxidizer Boost Pump)	307	307	313	313
WBPFB (Fuel Boost Pump)	52	52	83	83
WMPOB (Main Oxidizer Pump)	862	623	878	638
WMPFB (Main Fuel Pump)	327	366	521	567
WLPLB (Low Pressure Lines)	201	201	243	243
WHPLB (High Pressure Lines)	268	268	324	324
WPSSB (Pressurization System)	133	133	133	133
WHGMB (Hot Gas Manifold)	207	207	207	207
WIGNB (Igniters)	60	60	60	60
WCNTRB (Controller)	130	130	130	130
TOTAL	5305	4720	5708	5129

II, B, Task II - Engine Parametric Analysis (cont.)

The WEIGHT computer program will be used to generate parametric weight and envelope values over the parametric ranges of thrust and chamber pressure starting from the baseline engine data.

C. TASK III - ENGINE/VEHICLE TRAJECTORY PERFORMANCE ASSESSMENT

The mission/vehicle characteristics of the two stage baseline vehicle for this task have been determined, and are ready for review by NASA. The baseline vehicle and its mission is described as follows:

TARGET ORBIT - 150 nautical miles due East from Cape Kennedy

PAYLOAD - 900,000 to 1,000,000 lbm

CONFIGURATION - Two parallel stages. Orbiter with SSME type LO_2/LH_2 engines, and booster with LO_2/hydrocarbon engines. Flyback capability of booster to launch is desirable.

This vehicle closely resembles the current baseline vehicle for the NASA/DOE Satellite Power Station (SPS) studies, and an effort is underway to secure all relevant vehicle information (aerodynamic characteristics, weights, trajectories, etc.) from the NASA/LaRC.

D. TASK IV - BASELINE ENGINE SYSTEM DEFINITION

No activity scheduled.

III. CURRENT PROBLEMS

The heat transfer effort is presently scheduled to be completed on 7 March, but this will not cause a slip in the overall schedule.

IV. WORK PLANNED

A. TASK I

Complete the heat transfer effort and conduct the final power balance calculations for the cycle candidates. Establish component design requirements and operating conditions based upon the cycle balances in preparation for rating each engine cycle.

B. TASK II

Complete the engine weight and envelope parametrics, and initiate the engine performance parametrics.

C. TASK III

Establish the trajectory performance models for the baseline vehicle in preparation for evaluating each engine cycle.

D. TASK IV

No scheduled activity.